

SUPERCONDUCTING MICROWAVE ELECTRONICS AT LEWIS RESEARCH CENTER

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ABSTRACT

Over the last three years, NASA Lewis Research Center has investigated the application of newly discovered high temperature superconductors to microwave electronics. Using thin films of $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ and $\text{Tl}_2\text{Ca}_2\text{Ba}_2\text{Cu}_3\text{O}_x$ deposited on a variety of substrates, including strontium titanate, lanthanum gallate, lanthanum aluminate and magnesium oxide, a number of microwave circuits have been fabricated and evaluated. These include a cavity resonator at 60 GHz, microstrip resonators at 35 GHz, a superconducting antenna array at 35 GHz, a dielectric resonator filter at 9 GHz, and a microstrip filter at 5 GHz. Performance of some of these circuits as well as suggestions for other applications are reported.

INTRODUCTION

Investigations to determine space electronics applications of high temperature superconductor (HTS) at NASA Lewis Research Center were initiated soon after the discovery of superconductivity in ceramic oxides $\text{La}_{1-x}\text{Sr}_x\text{CuO}_y$ ¹ and $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ ² with transition temperatures 35 K and 93 K. Soon after their discoveries were made others found the Bi-Sr-Ca-Cu-O³ and Tl-Ca-Ba-Cu-O⁴ class of 100 K + superconductors. Since that time the properties of these superconductors became known and we concentrated our efforts on development of thin films of $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ and $\text{Tl}_2\text{Ca}_2\text{Ba}_2\text{Cu}_3\text{O}_x$ for space microwave applications. The use of HTS films in a microwave system requires development of thin films on microwave substrates which then can be patterned into desired microwave circuits like filters, phase shifters, ring resonators and delay lines. Such circuits are used in space communication, radar, and sensing systems.⁵ Small size, low loss, low power and light weight are desirable features for these circuits.

In this paper, we describe the development of high quality $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ (YBCO) and $\text{Tl}_2\text{Ca}_2\text{Ba}_2\text{Cu}_3\text{O}_x$ (TCBCO) thin films on microwave substrates carried out at NASA Lewis and also at various sponsored and cooperative facilities. The method of fabricating and the evaluation of various microwave passive circuits is presented. At the end future applications are also highlighted.

DEVELOPMENT OF THIN SUPERCONDUCTING FILMS

To obtain high quality superconducting thin films on suitable substrates for microwave applications the substrate lattice constants must be closely matched to those of the films and there must not be a detrimental chemical reaction between the substrates and the films. In addition, the film composition must be as close to the correct composition as possible. To date, very high quality films have been obtained by using several physical and chemical deposition techniques. Many of these techniques had required postannealing at high temperatures. This high temperature anneal causes chemical interactions at the film-substrate interface, making the film-substrate interface unsuitable for microwave application.⁶ To circumvent this problem, a laser ablation technique^{7,8} followed by an in situ annealing procedure has been pursued and developed for the growth of YBCO films. Also, for the growth of TCBCO films, sputtering and laser ablation techniques were chosen and funded at University of Cincinnati and University of Nebraska at Lincoln, respectively. Though, with both methods an ex-situ anneal with thallium over pressure was required.

Both YBCO and TCBCO films were evaluated for their microwave properties. The reasons why YBCO was selected were because it can be grown single phase easily and has no competing phases when the oxygen pressure is 1 atm or less. Its critical field can exceed 100 T at low temperatures and its critical current is greater than 2×10^6 A/cm² at 77 K. TCBCO films were chosen because the TCBCO phase has a transition of 125 K in bulk form and early properties of bulk TCBCO showed that the material had lower 1/f noise than YBCO. The progress to date on the growth and characterization of YBCO and TCBCO thin films is presented subsequently.

YBa₂Cu₃O_{7-δ} Films

At the beginning of the research three methods of producing YBCO films were investigated. They were sequential evaporation, coevaporation, and laser ablation. In the following paragraphs, we briefly describe the techniques and give references for them.

Produced by sequential evaporation. - One of the earliest attempts at The Ohio State University to produce YBCO films was by sequential evaporation of copper, barium fluoride, and yttrium and followed by a postanneal.⁹ This procedure did produce YBCO films that were mainly a-axis aligned, but the films generally were poor having low transition temperatures (T_c) and critical current density (J_c) values and high porosity.¹⁰ Nevertheless, this technique did allow us to set up the necessary equipment for investigation of the optical and microwave properties of HTS films.^{9,11,12}

Produced by coevaporation. - Coevaporation is being pursued jointly by Oberlin College and NASA Lewis. The film by this technique is grown at room temperature by coevaporating Cu, BaF₂, and Y from separate electron beam guns.¹³ Then the film is postannealed similar to the postannealed sequentially evaporated films. One of the advantages for coevaporation is that patterns with 2 μm lines can be formed by using photoresist and a lift-off technique. So far the films produced have had a high T_c of 90 K but J_c in the 5×10^5 A/cm² range at 77 K. The low J_c is due to the high temperature annealing conditions which cause a substantial amount of a-axis growth and porosity.

Produced by laser ablation. - The laser ablation technique⁷ has given us the best YBCO films to date. Films by this technique were produced at NASA Lewis and the technique has also been set up at The Ohio State University, successfully. The basic principle of laser ablation is that a short wavelength and short pulse duration laser beam is focused onto a YBCO target. This evaporates the surface of the target and produces a plasma plume. Since the pulse duration is very short there is very little heat transferred to the target preventing thermal melting of the target and the noncongruent evaporation of the individual atoms. Therefore, a stoichiometric composition of the target is ablated from the surface.

The best films on LaAlO₃ were c-axis aligned and had a T_c around 90.6 K immediately after deposition as determined by a standard four point resistance measurement. Resistance versus temperature behavior for a YBCO film is shown in fig. 1. Critical current density J_c versus temperature is shown in fig. 2. As can be seen, the value of J_c was 2×10^6 A/cm² at 77 K. The surface of the films was very smooth with some small structure of about 0.25 μm in size. This size of structure has been confirmed by scanning tunneling microscopy. In table I, we list the performance of YBCO and TCBCO thin films on various microwave substrates along with the microwave properties of these substrates.

Tl₂Ca₂Ba₂Cu₃O_x Films

TCBCO films on LaAlO₃ substrates have been made at University of Cincinnati and University of Nebraska at Lincoln. University of Cincinnati made their films by r.f. sputtering of a compressed 2223 powder target^{14,15} followed by an anneal in Tl vapors. The smooth, dense films have a T_c between 103 K to 107 K with a 6 K transition width. The films are a mixture of 2223 and 2212 phases. University of Nebraska made their films by laser ablation and have achieved a T_c as high as 115 K, see fig. 3, but typical T_c were around 108 K.¹⁶ But the films are not smooth and have some porosity. They used a compressed powder target of TlO₂, BaCuO₂, and CaCuO₂. Presently, they are exploring the use of a 2223 target to achieve a film that is denser and has a T_c above 120 K.

Microwave Characterization

Surface resistance (R_s) of superconducting film is a basic physical property that can be used to determine the quality of the film and is necessary for microwave device design. Currently, surface resistance values are obtained by cavity^{17,18} and stripline measurements¹⁹. These measurements are time consuming, and it would be worthwhile to correlate R_s with dc or low frequency measurements, such as dc conductivity above T_c, magnetic penetration depth, T_c, and a.c. susceptibility measurement; but so far there has been no consistent correlation reported between any of these measurements and R_s. The microwave conductivity (σ) is another physical property that can be measured. The conductivity for a superconductor is complex (σ = σ₁ + iσ₂) when the temperature is below T_c and it can be related to R_s and to the penetration depth (λ)²⁰.

Miranda et al.¹² have determined σ by measuring the microwave power transmitted through superconducting thin films in a waveguide experiment. From the value of σ₂ the magnetic penetration depth (λ) can be obtained. A summary of results of σ₁, λ₀, R_s for YBCO film on various substrates is shown in table II. The R_s for these films were calculated from σ₁ and λ. For YBCO on LaAlO₃ the R_s was 1.4x10⁻³ Ω which compares very well with other data.²¹ The surface resistance is an order of magnitude lower than that of copper up to 60 GHz.²¹ This demonstrates that with microwave transmission measurements one can obtain the R_s, λ, and σ of HTS films. These three properties are necessary for the determination of the quality of HTS films and the designing of microwave circuits.

FABRICATION

We have developed a method to fabricate microwave circuits and test devices for HTS films. The method is to use standard photolithography using negative photoresist and a "wet" chemical etchant. This etchant was either a 1 at % solution of bromine in ethanol or dilute phosphoric acid in water. In addition, circuits identical to the HTS circuits were made from patterned gold. This allows a direct comparison between HTS and gold circuits.

APPLICATION INVESTIGATIONS

The application of HTS to communication or radar systems does not only depend on the properties of HTS material but also the total system cost versus performance. The single most important issue for space communication is the possible need for cryogenic cooling. If HTS circuits must be cooled cryogenically then that cost in terms of power and weight must be considered along with the improved performance of the devices and any savings in weight and power from the replacement of standard equipment with HTS equipment. However, there are some missions, such as deep space probes that only would require passive cooling or other missions where cryogenic cooling is necessary for other functions, where this would not be an issue. Some of the

microwave applications and testing are discussed below. A brief description of each is made or referred to. The applications under investigation are resonators, filters, phase shifters, hybrid circuits, and antennae.

60 GHz Cavity

The surface resistance of HTS films can be calculated directly from the "Q" value of a resonant cavity experiment where one of the end walls of the cavity is replaced with the HTS film.¹⁸ This has been done at 60 GHz for YBCO films on LaGaO_3 and SrTiO_3 . The R_s values for the two films can be seen in fig. 5. These films were approximately 1 μm thick; therefore, being polycrystalline c-axis oriented films. The results obtained agreed with other²¹ results for YBCO films grown by laser ablation and sputtering but measured at different frequencies. This agreement confirms the f^2 dependence of R_s and that the microwave properties for polycrystalline films of YBCO is independent of whether the films are grown on SrTiO_3 or LaGaO_3 .

Resonator Circuits

HTS stripline ring resonators were fabricated on LaAlO_3 substrates.²² For measurement the resonators were mounted in a cosine tapered ridge waveguide to microstrip test fixture as shown in fig. 4. That structure was cooled by a closed cycle refrigerator. The resonators were measured by an HP8510 automatic network analyzer. The resonance frequency of the resonator changed rapidly with temperature just below T_c . This change was due to the change in the circuit reactance caused by the change in the magnetic penetration depth.²²

The best resonators measured to date and compared to gold is shown in fig. 6. The unloaded "Q" ranged from 2500 to 1000 at 20 and 77 K, respectively. This corresponds to a surface resistance value of 8 m Ω at 77 K at 35 GHz, a value two to three times better than copper at the same temperature and frequency.

Filters

Another candidate for application of HTS thin films is in the area of passive microwave filters. Taking advantage of the low losses for HTS film we have considered where they could be applied within a satellite transponder to improve performance. Based on results obtained to date on the performance of superconducting microstrip resonator circuits with high "Q" values as compared to an all metal microstrip resonators, we project the application of superconducting passive circuits as low loss, high "Q" filters¹³, high "Q" resonators, delay lines, power splitter, power combiners, and resonator stabilized oscillators.

Phase Shifters

In addition to these applications, extremely low loss phase shifters using superconducting switches are also feasible. In fig. 7, we show a phase shifter which utilizes superconducting-normal-superconducting switches in place of FET/diode switches. The switches are fabricated from high temperature thin films of YBCO. The switches operate in the bolometric mode with the film near its transition temperature. Radiation from a light source raises the temperature higher than the film's T_c and consequently causes the film to become resistive. When the light is "on" the microwave signal travels past the switch, but is reflected when the light is off. To achieve the desired phase shift, the pair switches on the same side is illuminated. Fig. 8 shows the predicted behavior for a 180° phase shifter with a R_s value that is the same as gold at 77 K and having a R_s of 100 $\mu\Omega$ in the normal state. It has an with exceptional narrow insertion loss envelope and excellent return loss.

Hybrid Semiconductor/Superconductor Device

The natural use of hybrid semiconductor and superconductor devices will be where III-V compound semiconductors, such as AlGaAs, InGaAs, and III-V heterojunction material, will be used at temperature around 77 K for devices that cannot operate or give the necessary performance at room temperatures. Some of these applications are for low noise amplifiers at frequencies above 22 GHz or solid state amplifiers above 70 GHz. Since these semiconducting devices will have to be cooled to 77 K there is no penalty in terms of the cost or reliability of the refrigeration to be paid to use superconductor devices. Therefore, it is natural to use HTS circuits in conjunction with III-V semiconductor devices to obtain the best performance of devices at these temperatures.

In fig. 9, we show an example of hybrid semiconductor/superconductor device for an ultra low noise receiver for satellite applications. This receiver takes the advantage of the excellent noise properties of AlGaAs HEMT technology and the low noise and resonator properties of superconducting transmission lines to achieve the ultra low noise and stable amplification.

Superconducting Phased Arrays

Superconducting antennas have long been imagined as extremely low loss devices. The use of superconductors to reduce the size of antennas to a fraction of a wavelength and to make super-directive arrays have been some of the more popular subjects. It has been shown recently, however, that of these various uses, the most practical use of superconductors in antennas will be in microwave and millimeter wave antennas.²³ To demonstrate the use of superconductors in such antennas, current research at NASA Lewis, in cooperation with Ball Aerospace, is focusing upon the fabrication and testing of a four element planar array at 30 GHz (fig. 10). The performance of this antenna will be compared to an identical array fabricated using gold instead of HTS.

CONCLUSIONS

We have demonstrated that rare-Earth oxide thin superconducting films can be deposited on various microwave substrates with critical temperature T_c above 77 K, critical current densities J_c above 10^6 A/cm², and low surface resistance. The films can be easily etched into microwave transmission line circuits. Microwave circuit ring resonator fabricated from a YBCO superconducting film on LaAlO₃ substrate showed "Q" values four times that for similar resonator made from a gold film. Several key HTS circuits such as filters, oscillators, phase shifters, and phased array antenna feeds are feasible in the near future. For technology to improve further, reproducible, large area films have to be grown on low dielectric constant, low loss microwave substrates. Tradeoffs between superconducting microwave circuits with cryogenic systems and normal metal microwave circuits will have to be quantitatively established to determine their suitability for advanced communication and sensor systems.

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TABLE I. - KEY PROPERTIES OF MICROWAVE SUBSTRATE MATERIALS
AND THE TRANSITION TEMPERATURE (T_c) FOR LASER ABLATED
 $\text{YBa}_2\text{Cu}_3\text{O}_7$ FILM ON THE VARIOUS SUBSTRATES

Material	Laser, T_c (K)	Dielectric constant	Loss tangent	Lattice size, \AA
Magnesium oxide (MgO)	88	9.65	4×10^{-4}	4.178 (100)
Lanthanum aluminate (LaAlO_3)	90	22	5.8×10^{-4}	3.792 (110)
Lanthanum gallate (LaGaO_3)	88	27	2×10^{-3}	3.892 (110)
Sapphire (Al_2O_3)	73	9.4	1×10^{-6}	5.111 (011)
Yttria stabilized zirconia (ZrO)	89	11.6	6×10^{-4}	3.8795 (100)
Silicon (Si)	--	12	10×10^{-4}	5.43 (100)
Gallium arsenide (GaAs)	--	13	6×10^{-4}	5.563 (100)

TABLE II. - THE REAL PART OF THE CONDUCTIVITY $\sigma = \sigma_1 + i\sigma_2$,
AND AT 77 K AND 33 GHz, THE CALCULATED R_s AT 5 GHz, THE
MAGNETIC PENETRATION DEPTH (λ_o) FOR $\text{YBa}_2\text{Cu}_3\text{O}_7$ FILMS ON
 LaAlO_3 , MgO, AND YTTERIA STABILIZED CUBIC ZIRCONIA (YSZ)

Substrate	Thickness, nm	σ_1 , s/m	R_s (Ω), 33 GHz	R_s (Ω), 5 GHz	λ_o , nm
LaAlO_3	177	2.5×10^5	1.8×10^{-3}	41×10^{-6}	360
MgO	350	1.2×10^5	5.9×10^{-3}	135×10^{-6}	530
YSZ	120	2.4×10^5	2.5×10^{-3}	57×10^{-6}	590

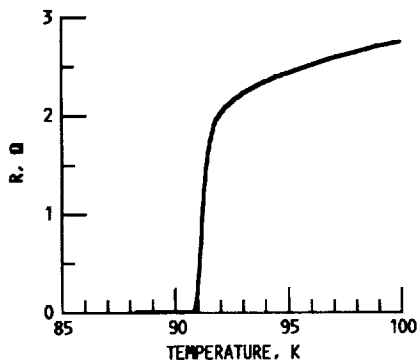


FIGURE 1. - D.C. RESISTANCE VERSUS TEMPERATURE OF LASER ABLATED $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ FILM ON LaAlO_3 .

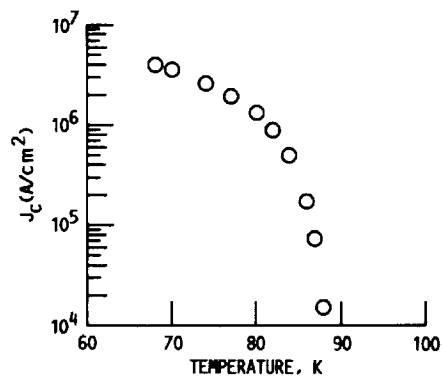


FIGURE 2. - CRITICAL CURRENT DENSITY OF LASER ABLATED $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ FILM ON LaAlO_3 .

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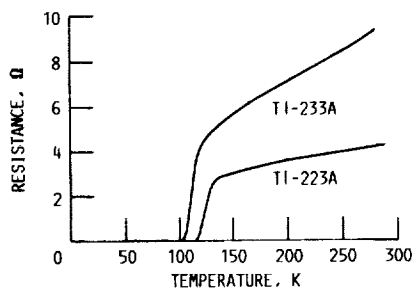


FIGURE 3. - D.C. RESISTIVITY VERSUS TEMPERATURE OF TWO $\text{Tl}_2\text{Ca}_2\text{Ba}_2\text{CuO}_x$ FILMS.

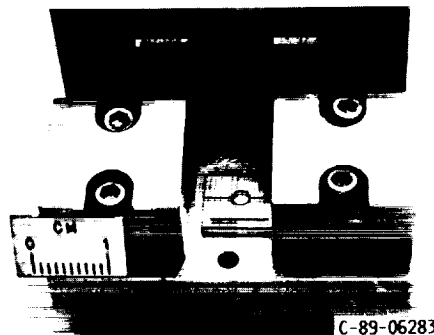


FIGURE 4. - WAVEGUIDE TEST FIXTURE USED FOR THE MEASUREMENT OF "Q" VALUES OF SUPERCONDUCTING RING RESONATORS.

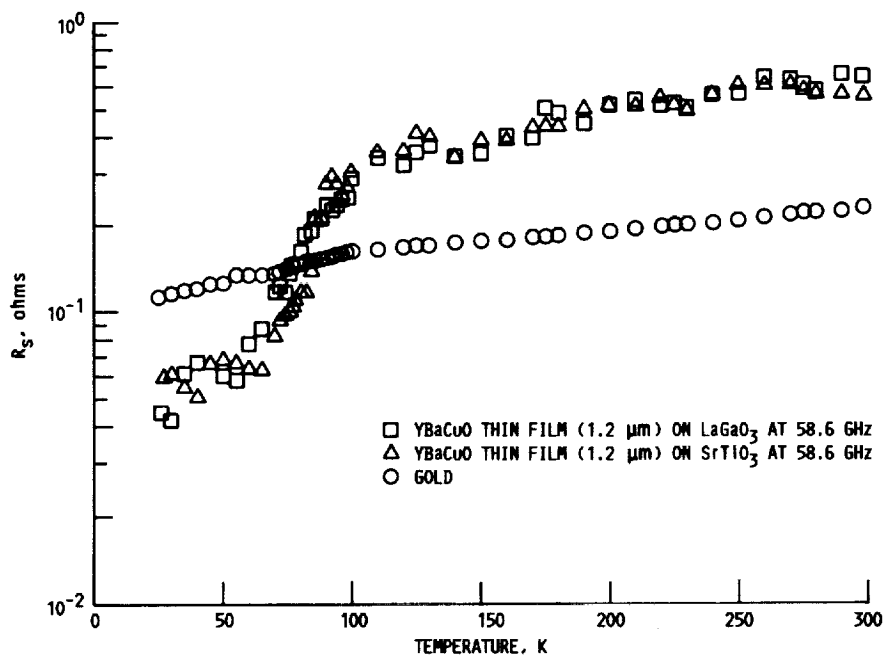


FIGURE 5. - SURFACE RESISTANCE (R_s) VERSUS TEMPERATURE FOR GOLD AND LASER ABLATED $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ FILMS ON THE INDICATED SUBSTRATES AS MEASURED IN THE 58.6 GHz GOLD CAVITY.

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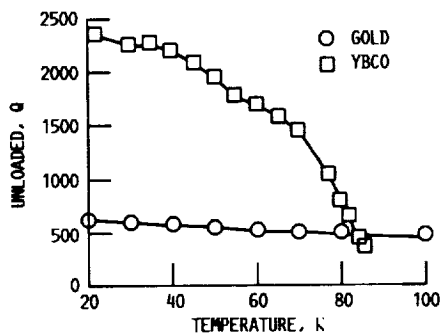


FIGURE 6. - 35 GHz RING RESONATOR UNLOADED "Q" VERSUS TEMPERATURE FOR GOLD AND LASER ABLATED $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ FILM ON LaAlO_3 .

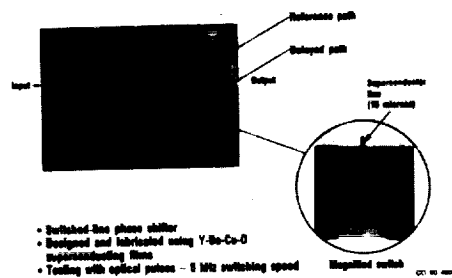
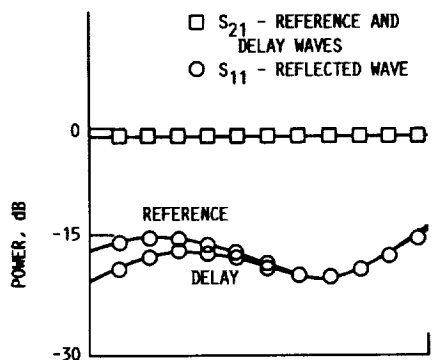
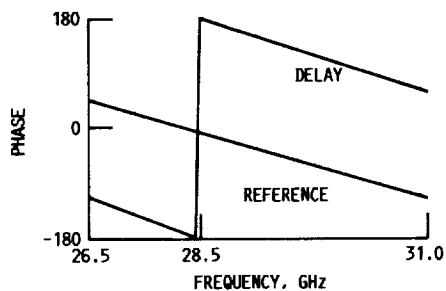


FIGURE 7. - OPTICALLY CONTROLLED SUPERCONDUCTOR PHASE SHIFTER.



(a) S_{21} AND S_{11} FOR REFERENCE, DELAY, AND REFLECTED WAVES.



(b) PHASE RESPONSE VERSUS FREQUENCY FOR REFERENCE AND DELAY PATHS.

FIGURE 8. - THEORETICAL RESPONSE FOR THE DESIGNED OPTICALLY CONTROLLED $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ PHASE SHIFTER AT 77K.

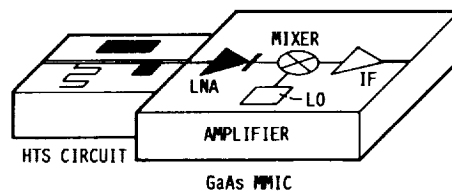
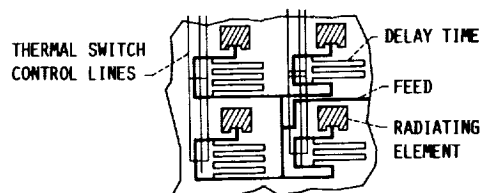


FIGURE 9. - SUPERCONDUCTING GaAs MMIC HYBRID RECEIVER.



4x4 ARRAY PRELIMINARY DESIGN

FIGURE 10. - PRELIMINARY DESIGN OF A THERMALLY SWITCHED PHASE ARRAY SUPERCONDUCTING ANTENNA FOR A 4x4 ARRAY.

SUPERCONDUCTIVE WIRES AND DEVICES FOR CRYOGENIC APPLICATIONS

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